4. Soil Mechanics Experiment

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The objectives of the Apollo 14 soil mechanics experiment are (1) to obtain data on the compositional, textural, and mechanical properties of lunar soils and the variations of these properties with depth and lateral displacement at and among the three Apollo landing sites; and (2) to use these data to formulate, verify, or modify theories of lunar history and lunar processes; develop information that may aid in the interpretation of data obtained from other surface activities or experiments (e.g., lunar field geology, passive and active seismic experiments, and modularized equipment transporter (MET) performance); and develop lunar-surface models to aid in the solution of engineering problems associated with future lunar exploration. The in situ characteristics of the unconsolidated lunar-surface materials can provide an invaluable record of the past influences of time, stress, and environment on the Moon. Of particular importance are such characteristics as particle size, particle shape, and particle-size distribution, density, strength, and compressibility.

The soil mechanics experiment relies heavily on observational data such as are provided by photography, astronaut commentary, and examination of returned lunar samples. Quantitative data sources are limited; however, semiquantitative analyses are possible, as shown in reference 4–1 for Apollo 11 and in reference 4–2 for Apollo 12. Such analyses are strengthened through terrestrial simulation studies[1] (ref. 4–3).

The results of the Apollo 11 and 12 missions have generally confirmed the lunar-surface soil model developed by Scott and Roberson (ref. 4–4); that is, the lunar soil is a predominantly silty fine sand, is generally gray-brown in color, and exhibits a slight cohesion. Evidence of both compressible and incompressible deformation has been observed. The lunar soil erodes under the action of the lunar module (LM) descent-engine exhaust during lunar landing, kicks up easily under foot, and tends to adhere to most objects with which it comes into contact. The value (or range in values) of the in situ bulk density of the lunar soil remains uncertain, although Apollo 11 and 12 core tube data and core tube simulations[2] give a best estimate of 1.7 to 1.9 g/cm^3. Limited direct evidence before the Apollo 14 mission suggested that some increase in soil strength and density occurs with depth beneath the lunar surface.

Observations at five Surveyor landing sites and the two previous Apollo landing sites indicate relatively little variation in surface soil conditions with location. Core tube samples from the Apollo 12 mission exhibited a greater variation in grain-

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[1] N. C. Costes, G. T. Cohron, and D. C. Moss: Mechanical Behavior of Simulated Lunar Soils Under Varying Gravity Conditions. Proc. Apollo 12 Lunar Sci. Conf. (Houston), Jan. 11–14, 1971. To be published in Geochim. Cosmochim. Acta.

[2] W. David Carrier III, Stewart W. Johnson, Richard A. Werner, and Ralf Schmidt: Disturbance in Samples Recovered With the Apollo Core Tubes. Proc. Apollo 12 Lunar Sci. Conf. (Houston), Jan. 11–14, 1971. To be published in Geochim. Cosmochim. Acta.

size distribution with depth than had been found for Apollo 11 core tube samples.

The Apollo 14 mission has provided a greater amount of soil mechanics data than either of the previous missions for two reasons. The crew covered a much greater distance during the extravehicular activity (EVA) than in previous missions, and the Fra Mauro landing site represented a topographically and geologically different region of the Moon. In addition, three features of particular interest to the soil mechanics experiment were new to the Apollo 14 mission—the Apollo simple penetrometer (ASP), the soil mechanics trench, and the MET. Each of these has been used to shed new light on lunar soil characteristics, and each is discussed in detail in this section.

Although the analyses and results presented in this report are still preliminary in nature, certain conclusions are already apparent.

(1) At the Apollo 14 landing site, a greater variation in soil characteristics exists laterally and within the upper few tens of centimeters than had been previously encountered.

(2) Although the lunar-surface material (uniform gray, fine silty sand) appears and behaves about the same at all locations, much coarser material (medium- to coarse-sand size) may be encountered at depths of only a few centimeters.

(3) Core tube penetrations, measurements with the ASP, and analyses of the interaction between the MET and the lunar surface have been useful for estimating soil properties and, in conjunction with the observations at the soil mechanics trench, for establishing that the lunar-surface soil strength increases with depth.

(4) In this report, as in previous reports, the lunar soil properties have been derived from estimates of penetration and force. The variation of soil properties indicated by the Apollo 14 mission reinforces the need for more quantitative and definitive measurements.

Descent and Landing

The Apollo 14 LM descended more steeply in the final stages of lunar approach than did the Apollo 11 and 12 spacecraft, although the descent profile was similar to that of Apollo 12 (ref. 4–2).

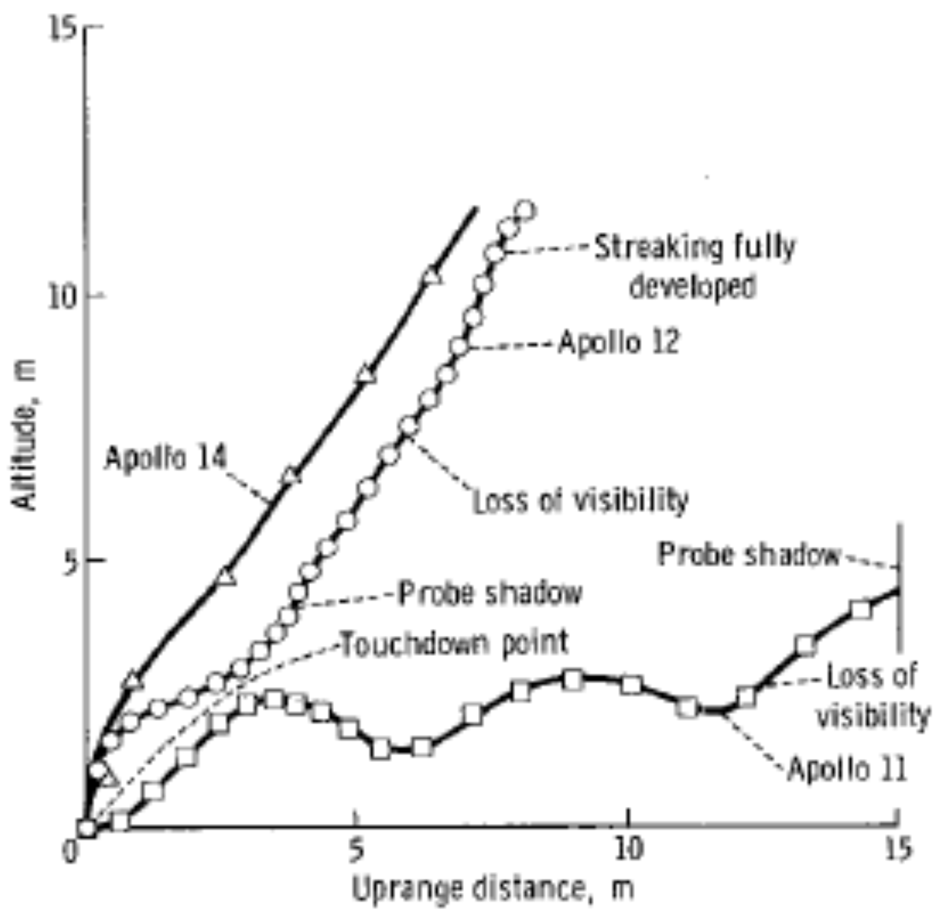

FIGURE 4–1.—A comparison of the final-approach profiles of the Apollo 11, 12, and 14 LM's.

A comparison of the final-approach profiles of all three spacecraft is presented in figure 4–1.

The final stage of the Apollo 14 descent proceeded from a pause of approximately 20 sec at an altitude of approximately 55 m above the lunar surface, while the spacecraft moved westward approximately 120 m until it was almost above North Triplet Crater. The altitude then decreased to approximately 30 m in the next 30 sec, as the LM continued another 120 m westward. The final approach of 35 sec took place at almost a 45° angle to the lunar surface. When the footpad probes made contact, the spacecraft was moving slightly west of north, according to the marks made on the surface by the probes (fig. 4–2). The landing was soft, and the astronauts reported little or no stroking of the shock absorbers. Approximately 2 sec after footpad touchdown, the descent engine was shut down. When the spacecraft came to rest, the $+Z$ leg (on which the ladder is mounted) was oriented approximately west 16° north, and the spacecraft was tipped forward in this direction (pitch) approximately 2°. At right angles to this direction, the LM was tilted down to the north, or in the $+Y$ direction (roll), approximately 7°.

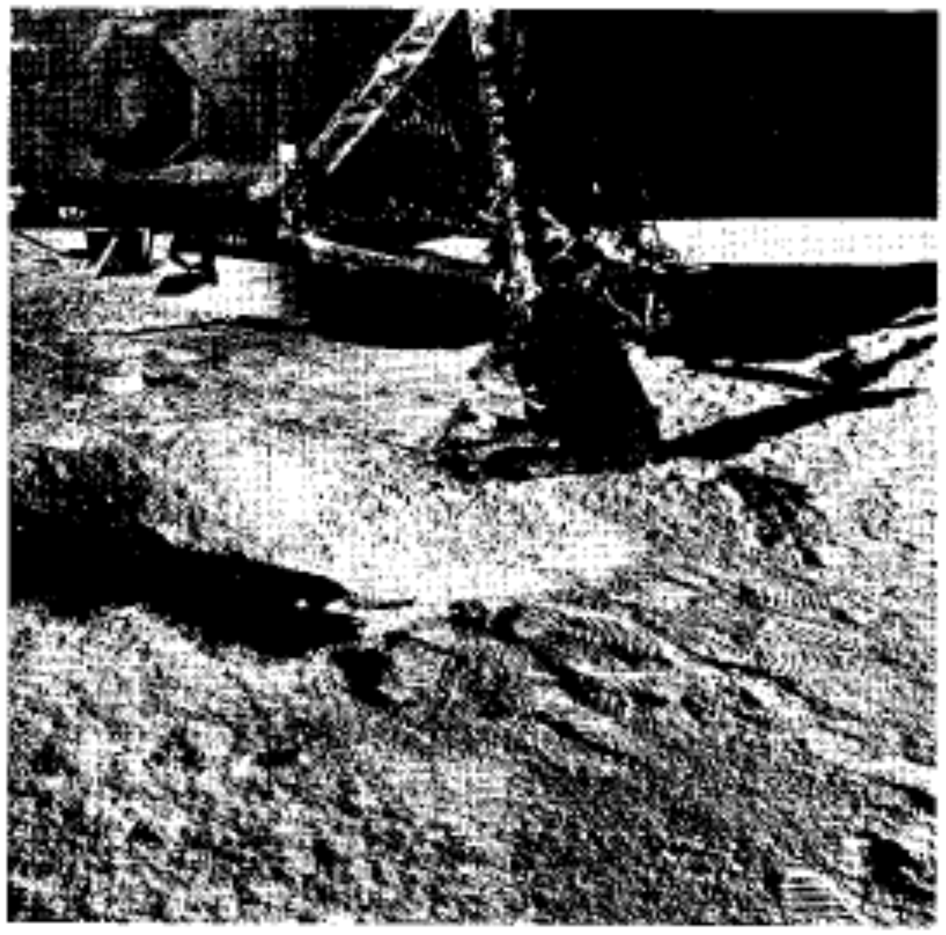

FIGURE 4–2.—Position of $+Y$ footpad embedded in the rim of a 2-m-diameter crater. The track of the contact probe on the surface appears somewhat east of south (AS14–66–9258).

The astronauts commented that blowing dust was first observed at an altitude of approximately 33 m and that the quantity of dust from that altitude down to the surface seemed less than had been encountered during the Apollo 11 and 12 landings. The dust apparently caused no visibility difficulties for the Apollo 14 crew. The Sun angle at landing was higher for the Apollo 14 mission than it had been for the Apollo 12 landing. A comparison of the descent motion pictures confirms the astronaut observations, in that the appearance of the blowing lunar-surface material during the Apollo 14 descent seems qualitatively similar to that observed during the Apollo 11 landing. Dust was first observed at altitudes of 24, 33, and 33 m for the Apollo 11, 12, and 14 landings, respectively. These observations occurred 65, 52, and 44 sec before touchdown, respectively. Because of the effect of Sun angle and spacecraft orientation, however, the appearance of the dust in the motion pictures may not be a reliable indication of the quantity of material removed.

After the landing, the astronauts reported that the lunar surface gave evidence of the greatest erosion in an area approximately 1 m southeast of the region below the engine nozzle. They noted that as much as 10 cm of surface material may have been removed during the landing. A distinct erosional pattern is visible in figure 4–3, which shows the area below the descent-engine nozzle. Except for a disturbed area in the left middle distance, the surface gives the appearance of having been swept by engine gases in the same way as had occurred on previous missions. The disturbed area may have developed as a consequence of a grazing contact of the $+Y$ footpad contact probe during the landing. It was noted in a previous report (ref. 4–1) that such a disturbance to the lunar surface breaks up the surface material and renders it more susceptible to engine-exhaust erosion.

In the Apollo 14 descent motion pictures, it is evident that the lunar surface remains indistinct for a number of seconds after descent-engine shutdown. This event was probably caused by venting from the soil of the exhaust gas stored in the voids of the lunar material during the final stages of descent. The outflowing gas carries with it fine soil particles that obscure the surface.

FIGURE 4–3.—Area below the descent-engine nozzle showing erosional features caused by the exhaust gas. The $-Y$ footpad can be seen in the distance (AS14–66–9262).

Some of the tilting of the spacecraft can be explained by an examination of the footpads. The $-Y$ (fig. 4–3) and $-Z$ footpads have penetrated the surface only to a depth of 2 to 4 cm, whereas the $+Y$ (fig. 4–2) and $+Z$ footpads have penetrated to a depth of 15 to 20 cm. The $+Y$ footpad penetration mechanism is clearly visible in figure 4–4; the footpad contacted and plowed into the rim of a 2-m-diameter crater. The motion of the footpad through the soil caused a buildup of a mound of soil on the north side of the pad. The height of the mound is somewhat higher than the actual penetration depth of the footpad. The astronauts reported that the $+Z$ footpad, which is in the shadow of the LM, also landed on the rim of a small crater and exhibited appearance and penetration characteristics similar to the appearance and penetration characteristics of the $+Y$ footpad. The mechanical properties of the soil, which are inferred from the response of the soil to the landing (which occurred with little or no shock-absorber stroking) and from the appearance of the soil in the footpad photographs, appear to be similar to the mechanical properties of the lunar material on which the Apollo 11 and 12 LM's landed.

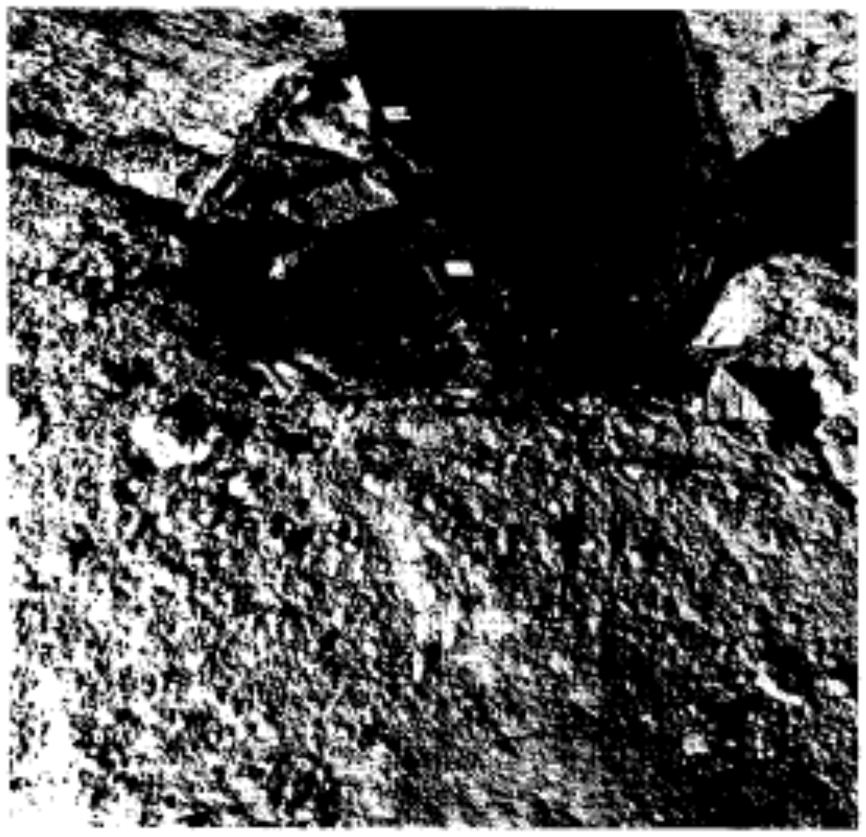

FIGURE 4–4.—The $+Y$ footpad embedded in the lunar soil. The gold foil surrounding the landing leg is probably the protective wrapping on the MET (AS14–66–9234).

The penetration of the $+Z$ and $+Y$ footpads caused 1° to 1.5° of LM tilting in the westerly and northerly directions. Consequently, at the landing site, the strike of the lunar-surface slope is approximately west 16° north, and the dip is approximately 5.5° in the direction north 16° east.

Extravehicular Activities

General Observations

The behavior of the surface soil, as observed during the two EVA periods, was in many respects similar to that observed during earlier missions. The soil could be kicked up easily during walking but would also compress underfoot. Footprints ranged in depth from 1 to 2 cm on level ground to 10 cm on the rims of fresh, small craters. The MET tracks averaged 2 cm and ranged up to 8 cm in depth. Soil conditions evidently had less influence on the mobility of the astronauts and the MET than did the topography.

Patterned ground ("raindrop" pattern) was fairly general, except near the top of Cone Crater. The factors responsible for the development of this surface texture are not yet known, although the texture is probably related to the impact of small particles on the lunar surface.

As has been observed during previous missions, disturbed areas appear darker than undisturbed areas as may be seen in the background of figure 4–5. Smoothed and compressed areas (e.g., MET tracks and astronauts' footprints) are brighter at some Sun angles, as shown in figure 4–6. In some instances, it was difficult for the astronauts to distinguish between small, dust-covered rocks and clumps or clods of soil. The tops of many of the large rocks were free of dust, although fillets of soil were common around the bottom. The astronauts commented that the major part of most large rocks appeared to be buried beneath the surrounding lunar surface. They also noted no obvious evidence of natural soil-slope failure on crater walls.

Adhesive and Cohesive Behavior

As on previous missions, dust was kicked up by walking. Objects brought into contact with the